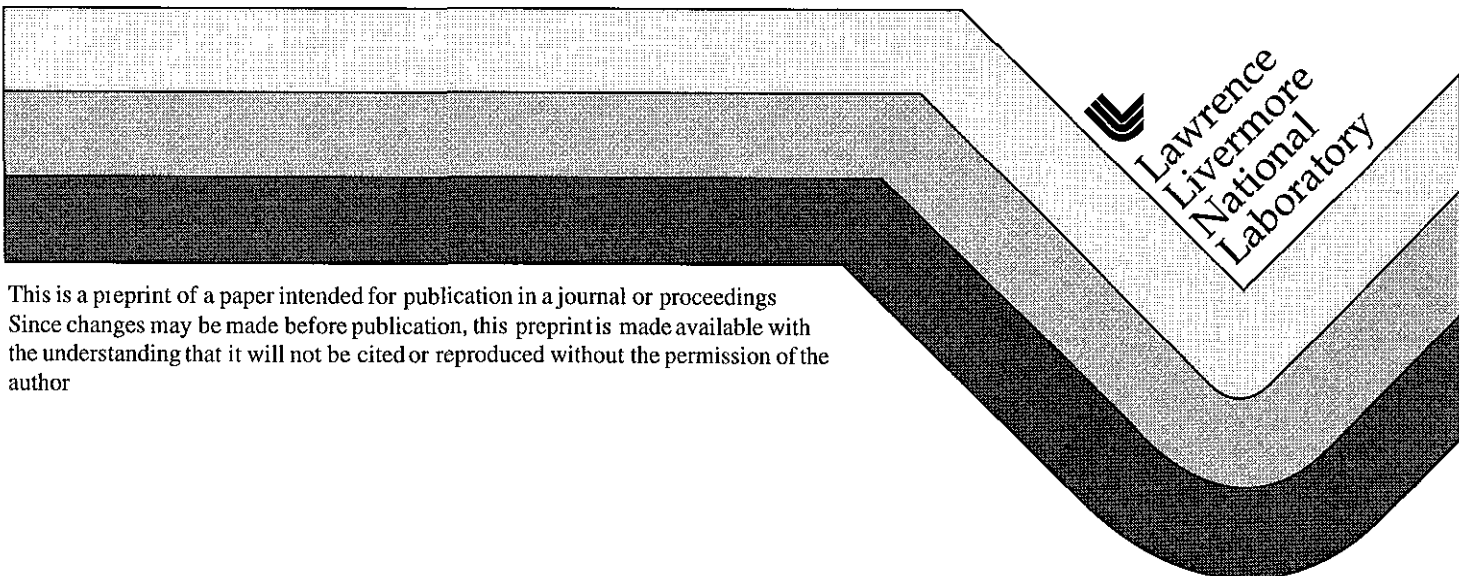


Development of Practical Damage-Mapping and Inspection Systems

F. Rainer, R. K. Dickson, R. T. Jennings, J. F. Kimmons,
S. M. Maricle, R. P. Mouser, S. Schwartz, and C. L. Weinzapfel

This paper was prepared for submittal to the
Third Annual International Conference on
Solid State Lasers for Application (SSLA) to Inertial Confinement Fusion (ICF)
Monterey, CA
June 7-12, 1998

August 18, 1998



DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Development of practical damage-mapping and inspection systems

F Rainer, R K Dickson, R T Jennings, J F Kimmons,
S M Maricle, R P Mouser, S Schwartz, C L Weinzapfel

Lawrence Livermore National Laboratory
P O Box 5508, L-487, Livermore, CA 94551-9900

ABSTRACT

We have developed and are continuing to refine semi-automated technology for the detection and inspection of surface and bulk defects and damage in large laser optics. Different manifestations of the DAMOCLES system (Damage and Artifact Mapping Of Coherent-Laser-Exposed Substrates) provide an effective and economical means of being able to detect, map and characterize surface and bulk defects which may become precursors of massive damage in optics when subjected to high-fluence laser irradiation. Subsequent morphology and evolution of damage due to laser irradiation can be tracked efficiently. The strength of the Damocles system is that it allows for immediate visual observation of defects in an entire optic, which can range up to 1-meter dimensions, while also being able to provide digital map and magnified images of the defects with resolutions better than 5 μm .

Keywords: damage, damage mapping, laser-induced damage, optics

1. INTRODUCTION

Damage to large optics, ranging near 1-meter dimensions, in laser systems such as the National Ignition Facility (NIF) currently being constructed at the Lawrence Livermore National Laboratory (LLNL) can yield catastrophic consequences if not monitored and controlled. Damage can originate from optical defects $\leq 5\text{-}\mu\text{m}$ in size in the optics themselves, from modulation due to upstream obscurations, or from naturally developing hot spots in the large-area laser beam cross sections. The Beamlet laser at LLNL, a single-beam prototype of the 192-beam NIF has employed an on-line diagnostic system to monitor the development of damage at vulnerable positions such as at spatial filter lenses to preclude damage from growing undetected to sizes large enough to cause catastrophic failure of the vacuum vessel.¹ At the left of Fig. 1 we show a typical photographic image of such a lens on Beamlet. However, the busy nature of the image means that only relatively large damage can be resolved. Typically, hand-drawn maps (center) had been generated on Beamlet to keep track of damage growth by a very labor-intensive and subjective process. The same map (right) generated off-line by Damocles shows very precise locations of damage which can be further quantified for size and morphology by a long-working-distance microscope.

Different manifestations of Damocles systems are currently being used at LLNL and at commercial vendor sites where optics are being fabricated for NIF.² These systems are being employed to (1) detect bulk defects and damage in fused silica and KDP substrates and lenses, (2) refine polishing and diamond-turning processes to raise laser-induced damage thresholds of surfaces, (3) track growth of damage after successive laser irradiations and the propagation of damage from one optical component to the next, and (4) inspect laser-glass slabs for the presence of platinum inclusions and for the effects of surface contamination in amplifier housings.

2. DAMAGE MAPPING SYSTEM CONFIGURATION

The mapping and inspection of damage or artifacts is accomplished by a two-step process employing hardware illustrated in Fig. 2. The black component represents the test optic mounted in a frame. The frame is designed to also support a series of linear, fiber-optic light lines which illuminate the optic through its four edges. This highlights bulk and surface damage sites which penetrate into the bulk. The damage can then be photographed by a

scanning, linear-array, mega-pixel camera with resolutions of up to 7520 x 6000 pixels. These elements (shown in gray), together with appropriate baffling, comprise the tools for the first step of the process to provide a precise digital map of all damage sites in the optic. The cross-hatched components are those used in the second step. Rear illumination by a fiber-optic light source allows high-resolution images of each damage site to be photographed using a long-working-distance microscope. The microscope is automatically directed to each site by computer utilizing the address of the site obtained in step one. In some instances the microscope is moved via three orthogonal translation stages (as is shown in the figure), in other instances we moved the optic itself via a large-scale translation stage.

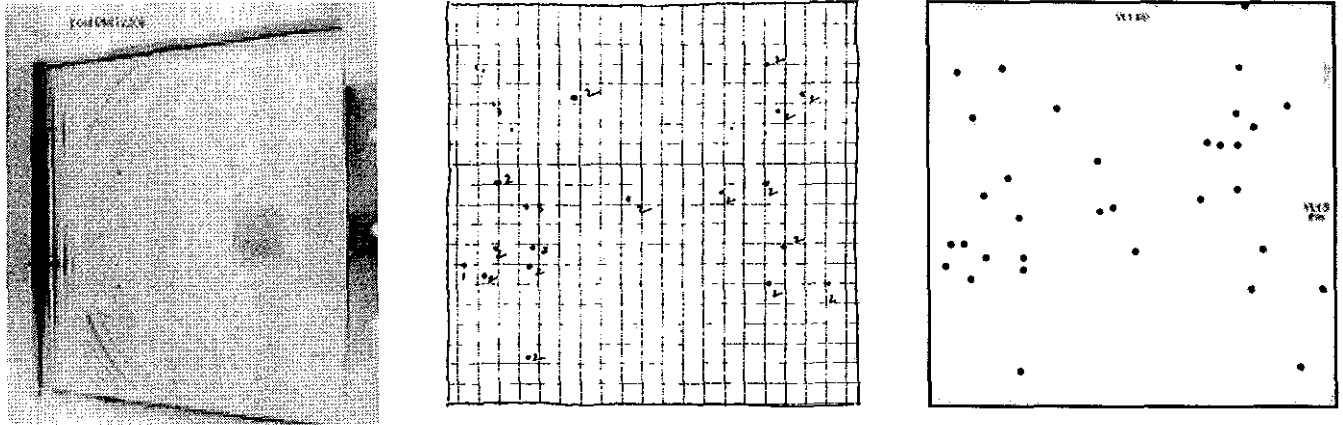


Fig. 1 Pinpoints of damage in an on-line photograph of a Beamlet lens (left) are quantified in a hand-drawn map (center). The image at the right shows the precise map of the same lens generated off-line by Damocles.

The procedure employed in generating the digital map of step one is illustrated in Fig. 3. In the top image, an exposure is made of the optic which takes about 20 minutes at the slowest possible scan rate in order to be able to detect even subtle artifacts. Bright artifacts will be saturated, but this is not important since only the address of the damage site is being determined in the mapping process. A second, relatively low-level exposure is made which takes about one minute. This is used to define the precise optic rotation of the edges, the coordinate origin and the optic size. The center image shows the optic precisely rotated to orthogonal axes and sized to the exact optic dimensions as defined by the added edge lines. The exposure is inverted for more convenient viewing and printing. The bottom image shows typical, manually-added demarcations under higher magnification to highlight all damage sites and raster-scanned rectangular areas. This again is only for convenience of viewing a printed copy of the map.

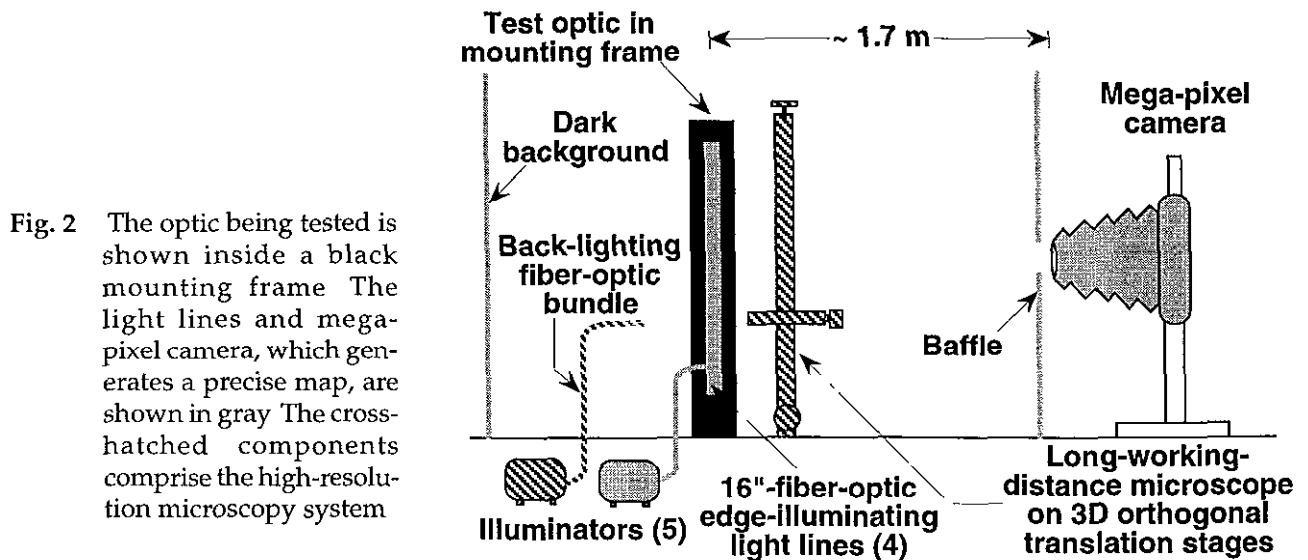


Fig. 2 The optic being tested is shown inside a black mounting frame. The light lines and mega-pixel camera, which generates a precise map, are shown in gray. The cross-hatched components comprise the high-resolution microscopy system.

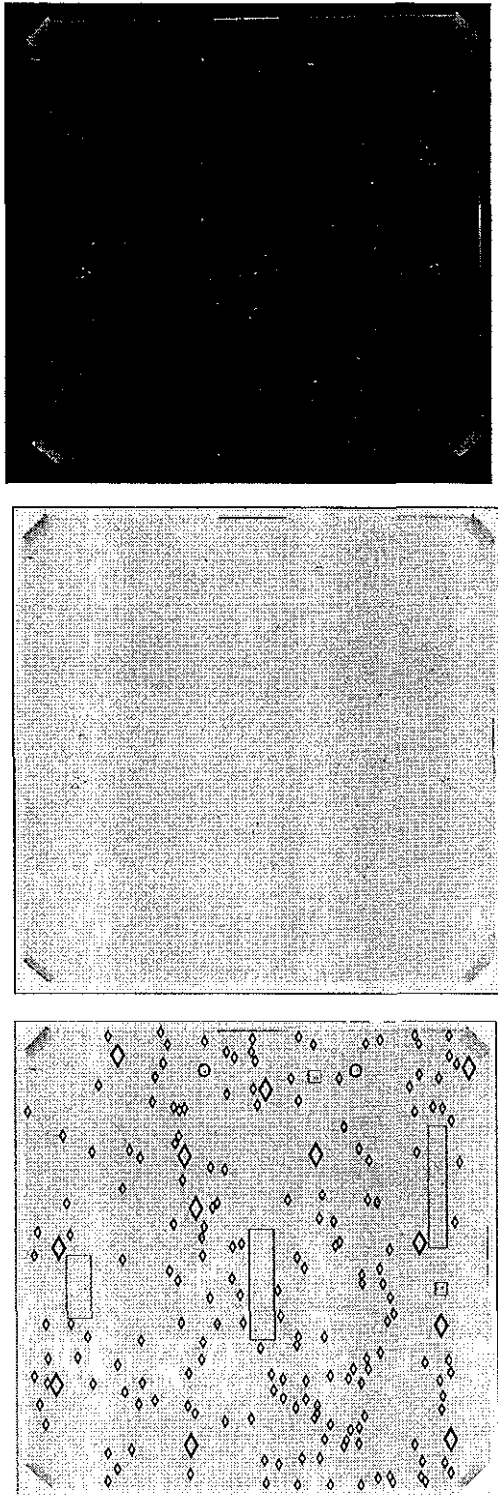


Fig. 3 The mapping process is illustrated in three stages to show how an accurate, full-sized map of an optic can be generated

In the second step a long-working-distance microscope is automatically directed to each damage site to generate a high resolution image of the artifact at the address determined in step one. Since step one only generates a two-dimensional image the microscope must be focused to the precise location of the artifact within the bulk of the substrate or on either surface. Some parallax does occur depending on how deeply into the substrate the artifact resides. These exposures are made primarily with back illumination, but the edge illumination from the light lines can help provide contrast. Fig. 4 highlights a typical location of an artifact (in this case a 100- μm bubble) at its mapping address with its actual address and high-resolution image shown in the inset. There is good agreement between the two addresses so that all mapped artifacts can be readily located and photographed at high resolution.

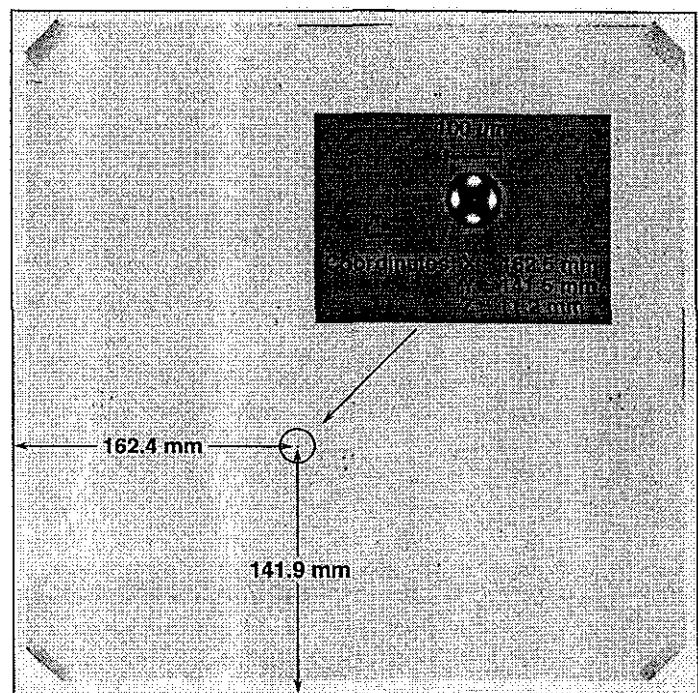


Fig. 4 The location of a typical artifact is shown on the map with its high-resolution image displayed as an inset

The morphology and sizes of detectable damage and artifacts can be quite varied. We show in Fig. 5 some typical examples of these, all at the same magnification as noted by the scale in the first image. The top row of images shows bulk-related artifacts or damage which include a bubble (note the four bright reflections from the four light lines), an inclusion with an index gradient around it, an inclusion after having been irradiated by a high-fluence laser shot, and massive, rear-surface, laser-induced damage due to a bulk inclusion near the rear surface. Typical surface effects are illustrated in the lower row of images. These include major laser-induced surface damage super-imposed on a pre-existing scratch which has also been enlarged by damage, a series of massive damage spots probably on an invisible sub-surface scratch, surface contamination (probably saliva), and a large piece of dust. As will be

shown later, surface contamination is detected much more readily with the light lines at grazing incidence from the surface rather than through the edges of the optic

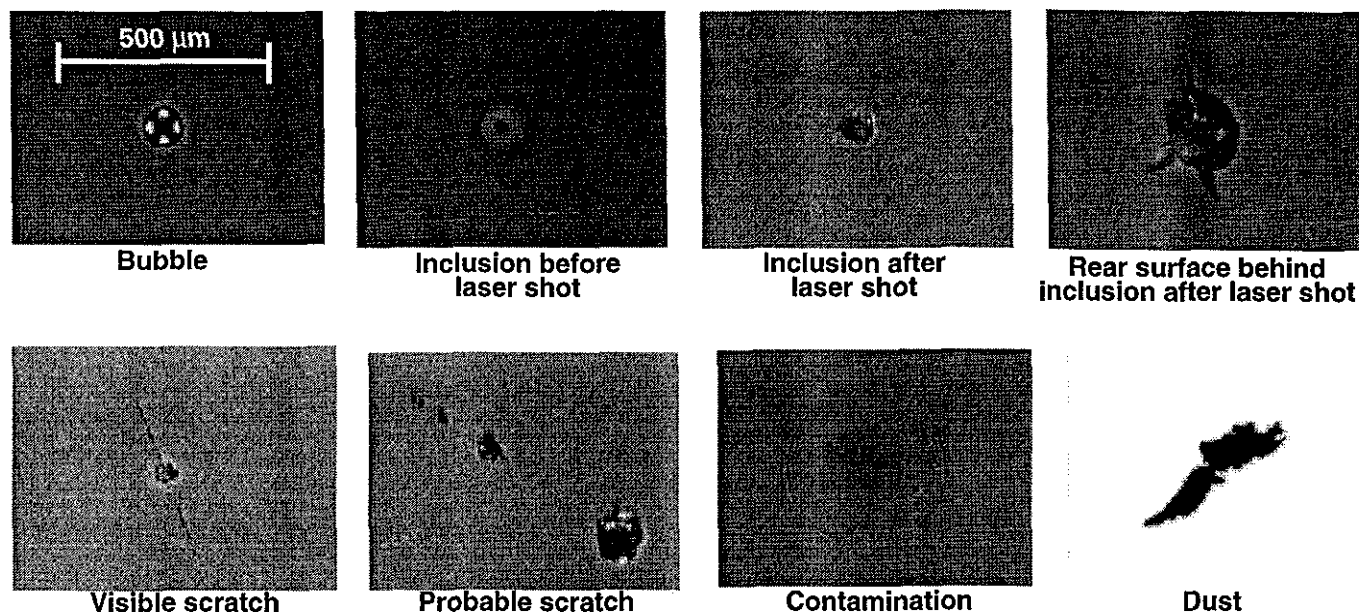
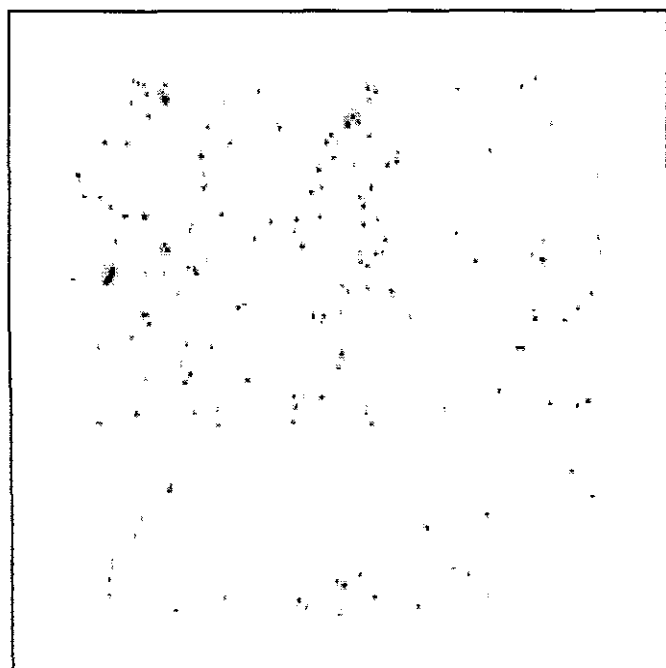


Fig. 5 Typical high-resolution digital images are recorded using a long-working-distance microscope. The upper row shows bulk-material artifacts and induced damage. The lower row shows substrate surface artifacts and induced damage.



Number of particles: 717 detected
730 actual
X dim. (mm) 390.000 X mm/pixel 0.085
Y dim. (mm) 390.000 Y mm/pixel 0.085

Particle number	Area calibrated	Center of mass (X)	Center of mass (Y)
1	0.029	318.24	364.895
2	0.022	47.699	363.639
3	0.007	47.247	359.349
4	0.423	207.107	358.324
5	0.05	100.736	357.075
...
...

Fig. 6 A map of a large (39-cm square), heavily damaged optic plus a printout of a subset of the address of each artifact determined automatically by computer.

3. DAMAGE MAPPING APPLICATIONS

The Damocles systems have been employed to address a wide variety of damage and contamination issues both at LLNL and by external vendors. Some of these are detailed in the following sections.

3.1 Mapping of damage due to laser irradiation

In Fig. 6 we show an example of a 30-cm optic that was peppered with a large number of damage sites after being irradiated at high fluences over the entire area on the Beamlet laser. When blown up to full size, and under even higher magnification, 730 defects were detected which ranged in size from $\sim 5 \mu\text{m}$ to several mm. The table to the right shows a subset of the results of the automated detection system which we have developed. In less than one minute the entire digital image was scanned for artifacts. The automated detection program located 717 of the sites and determined precise addresses. It also calculated an approximate size of each artifact. Only 1.8% of the dimmest artifacts (presumably the smallest) failed to be detected automatically.

Before the development of Damocles, a small-beam raster scan of such a large optic would have taken more than a day. Examining each site in detail through the bulk of the substrate before and after laser irradiation would have taken considerably longer. Random damage testing of a limited area in a shorter time would probably not have located vulnerable sites in such a large optic. As an example, assume that each of the 730 damage sites was generated by artifacts with volume dimension of $100 \mu\text{m}$. Every microscopic examination site typically has volume dimensions of about 1 mm^3 . Then for a 39-cm square optic, 5 cm thick, the 730 sites where damage was observed would only have occupied 730 mm^3 or about 0.01% of the total volume of the optic. The occluded area of the 730 artifacts themselves would only have been 7.3 mm^2 or about 0.005% of the area of the optic. It would take more than 200 shots at random sites to statistically hit just one of these damage sites.

The serious consequences of undiagnosed damage can be shown in the images of Fig. 7. A bulk inclusion of only $30 \mu\text{m}$ in size can yield a damage site on the rear surface ten times larger after only one shot with high fluences at 355 nm. After several shots such a site can grow another order of magnitude. We will not utilize vacuum barriers that are subjected to high-fluence irradiation in the UV, but even in the IR mm-sized damaged induced by laser irradiation has produced catastrophic failure in vacuum spatial filters.

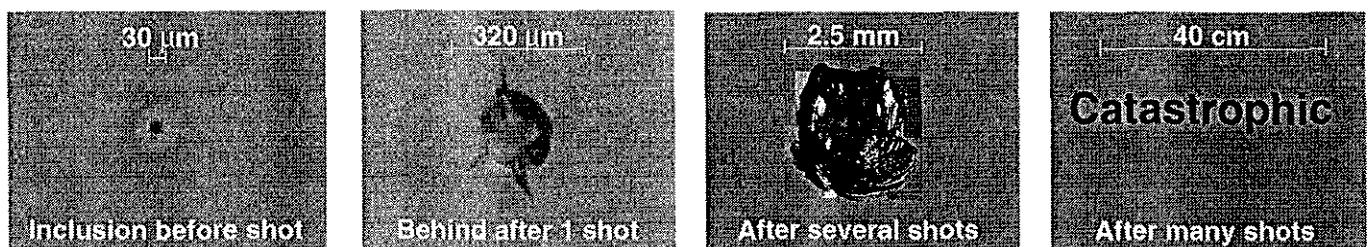


Fig. 7 The effects of small isolated artifacts can result in catastrophic consequences with successive shots. Other than full-volume interrogation of an optic can result in such sites going undetected.

3.2 Accurate overlaying of successive damage maps

By generating a very accurate map of all artifacts within an optic, or a succession of optics, we have been able to make assessments of whether particular artifacts will become nucleation sites for laser-induced damage, or whether modulation due to obscuration in one optic will generate damage in a successive optic downstream. Fig. 8 shows an example of the latter case where we examined damage in a KDP doubler, situated next to a KD*P tripler, and finally followed by a focusing lens. In this particular case we observed that there was no propagation of damage from one optic to the next. However, in more serious cases, we have in fact observed footprints of damage from one optic superimposed on another.

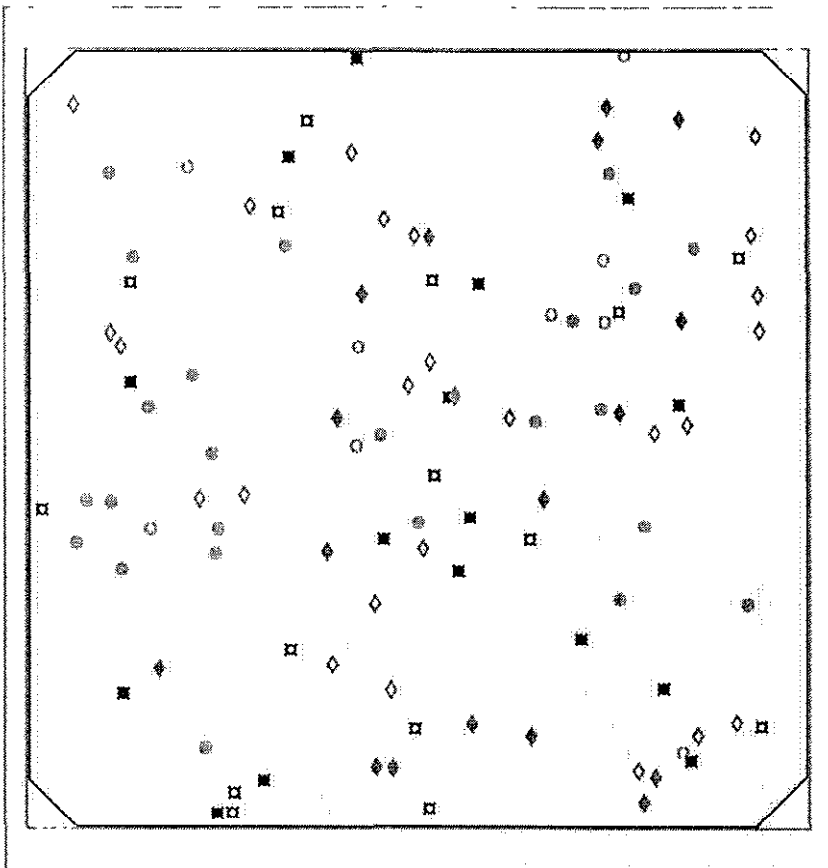


Fig. 8 The mapping of three successive elements in a laser chain showed that no damage propagated from one optic to the next. The image shows the superposition of damage from a KDP doubler (squares), a KD*P tripler (diamonds), and a final focus lens (circles). Filled symbols represent major damage.

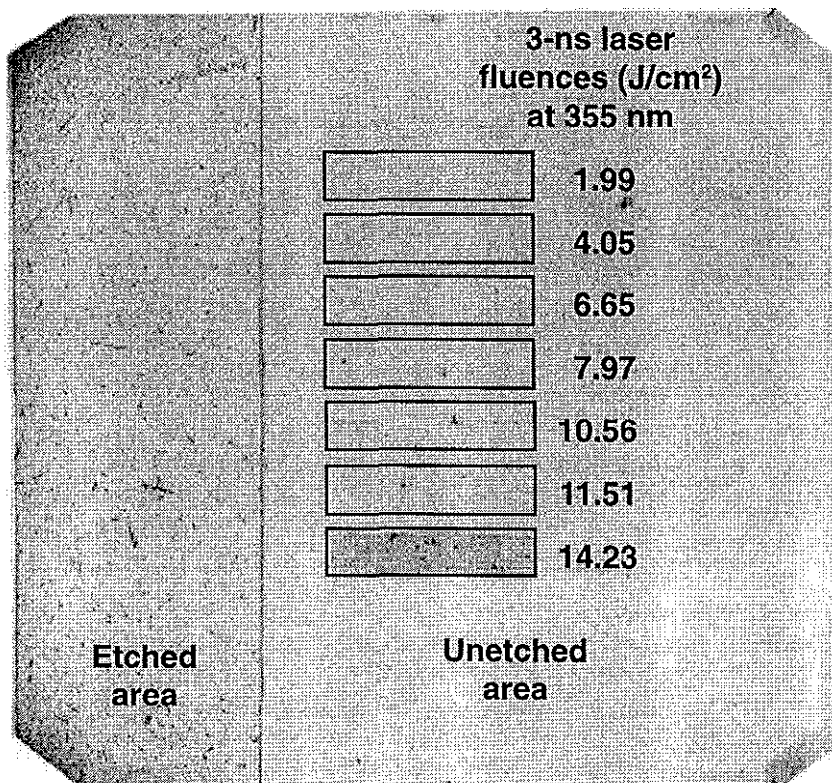


Fig. 9 Automated mapping helps expedite developmental damage tests over larger areas. In this case seven separate areas, each 2 cm x 10 cm, were raster scanned with a small laser beam at successively higher fluences.

3.3 Large-area damage tests with rastered small beams

By being able to detect damage quickly in relatively large volumes we have increased the efficiency with which we can conduct developmental damage tests using larger, more representative test areas. Typical random tests used to be conducted on 10 to 100 sites with a small laser beam on the order of 1 mm in size. Rastering allows larger areas to be irradiated, but the detection and correlation of artifacts and damage before and after laser irradiation is a very time-consuming process. Fig. 9 shows a typical experiment in which areas on the order of 2 cm x 10 cm were able to be assessed accurately both before and after laser irradiation at successively higher fluences.

3.4 Fiber optics illuminate laser-glass slabs for platinum and damage detection

Detection for platinum inclusions in laser-glass slabs used to be a painstaking task using high-temperature, hand-held lamps. The fiber-optic light lines designed for the Damocles systems are now employed as the default illumination technique. Not only do they generate far less heat, but they also illuminate the entire slab at one time with sufficient white light to detect laser-induced damage due to platinum inclusions. Fig. 10 shows a schematic of how two layers of light lines surround a laser slab. The slab is pneumatically lowered into a framework which houses the light lines and their power sources.

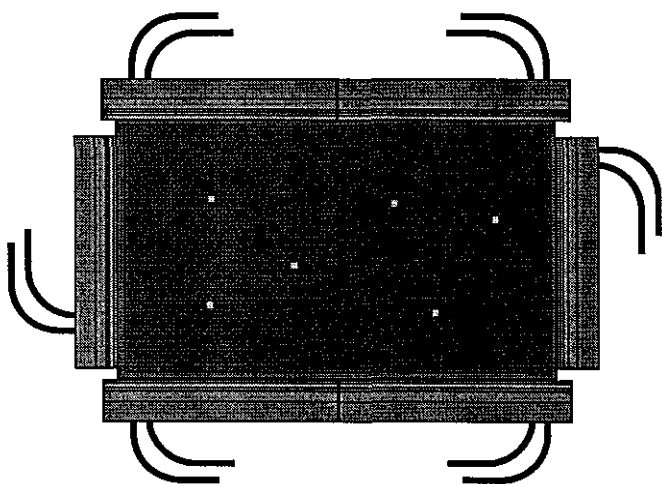
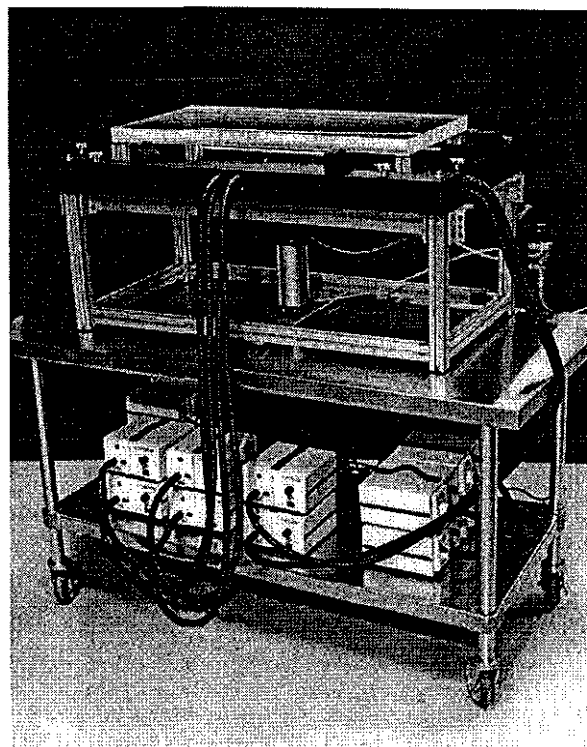


Fig. 10 At the left is a schematic drawing of the cool illumination of laser-glass slabs to detect platinum inclusions. The slab and 12 light fixtures are mounted in an assembly table shown at the right.



3.5 Other damage and contamination detection techniques

Damocles lends itself to be implemented for a variety of other diagnostic techniques which are being considered. Fig. 11 shows examples of some of these. The image at the top shows a fused silica substrate that was deliberately contaminated with a high density of surface artifacts. The right half of the scan of the substrate only saw edge illumination which highlighted primarily bulk artifacts. The left half of the scan was illuminated from the front at grazing incidence. The high density of surface contamination now became very apparent. The effects of more subtle surface contamination in laser amplifiers is currently being diagnosed with Damocles. In the center photograph we show that scratch-dig assessments can be made for large surface areas which can resolve scratches such as this one $< 5 \mu\text{m}$ wide. The lower image shows a potential application for detecting flaws at the interface between

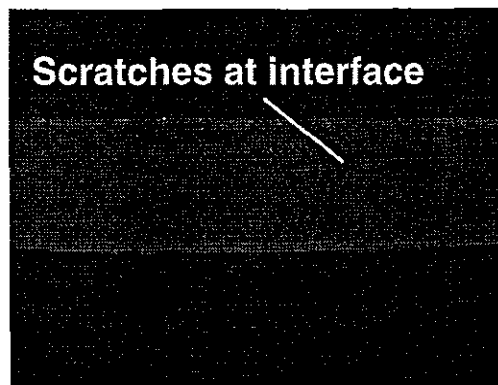
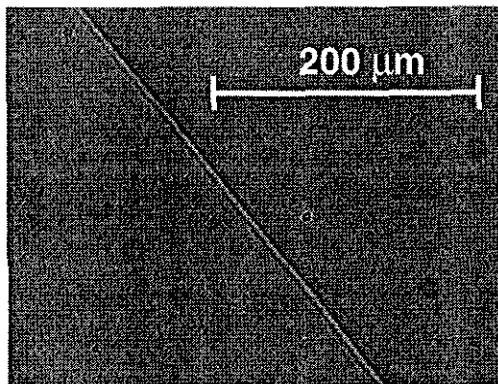
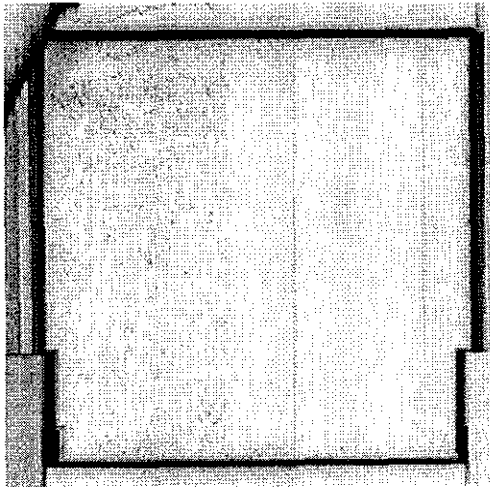


Fig. 11 Damocles lends itself to diagnosing other damage and contamination issues. The top image shows surface contamination highlighted by grazing illumination for the left half of the substrate, the center image shows that scratches can be resolved to better than $5\ \mu\text{m}$, the bottom picture points out subtle scratches at the edge-cladding bond of a laser-glass slab

laser-glass slabs and edge-cladding. Although the image does not reproduce well here, subtle scratches are readily detectable as well as pits, dirt, fingerprints and minor delaminations which can cause the edge-cladding to fail under high-temperature flashlamp loading.

4. CONCLUSIONS

Multiple applications of Damocles have made it a definitive tool for large-optic damage and artifact assessment. We are currently utilizing two full systems at LLNL and two subsystems at laser-glass vendors. The systems have been employed to track damage due to bulk inclusions and surface defects both before and after laser irradiation. This in turn provides rapid feedback to substrate polishing vendors working on raising damage thresholds at 355 nm. Similarly, large frequency conversion crystals have been mapped successfully at LLNL and may ultimately be examined with a dedicated mapping system. The linear light-line illumination technique has now been adopted as the default detection technique for platinum inclusions in laser-glass slabs. Variations of Damocles can be employed as back-up systems to assess surface contamination, to conduct scratch-dig measurements, and to detect edge-clad bonding faults.

5. ACKNOWLEDGMENTS

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

6. REFERENCES

- 1 C. E. Thompson, D. E. Decker and C. F. Knopp, "Optics damage inspection for the NIF," SPIE proceedings for this conference, June 1998.
- 2 F. Rainer, "Mapping and inspection of damage and artifacts in large-scale optics," *Laser-Induced Damage in Optical Materials* 1997, SPIE Vol. 3244, pp. 272-281, Oct. 1997.